FINAL REPORT
Blue Whale Behavioral Response Study & Field Testing of the New Bioacoustic Probe

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LONG-TERM GOALS

Task 1: Blue Whales Behavioral Response Study

The behavioral response of large whales to commercial shipping and other low-frequency anthropogenic sound is not well understood. The PCAD model (NRC 2005) for assessing sound impacts on marine mammals calls for studies on noise source characteristics and the behavioral impact of specific sources on individual animals. Our goal was to understand the vocal and behavioral response of individual blue whales to high-intensity ship noise and close ship approach, resulting from

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the close geographic association between known foraging grounds and commercial shipping lanes off the coast of California. To accomplish this goal we deployed acoustic recording tags and GPS recording tags on blue whales within and near the shipping lanes while concurrently monitoring shipping traffic using the Automatic Identification System (AIS).

Task 2: Field testing the new Bioacoustic Probe:
Tagging studies of odontocetes have yielded incredible insights into the diving, movement, and daily activities patterns of several species. Missing from most of these studies has been information on the acoustic environment in which the animal is living and the sounds produced by the animals during different activities. Our goal was to field test the new Acousonde on a variety of species for the purposes of understand how this tag may be used to address questions relating to diving behavior, vocal behavior, and swimming mechanics. Those field deployments and a detailed calibration of the acoustic systems within the tag have provided valuable feedback necessary to refine the operation of the tag for robust field operation in the future.

OBJECTIVES

Task 1: Blue whale behavioral response study:
Our primary objective for this task was to determine how blue whales respond to close approach of ships and exposure to high intensity ship noise including changes in diving, feeding, and calling behavior.

Task 2: Field testing the new Bioacoustic Probe
Our primary goal is to evaluate the functionality of the tag and to begin collection of vocal and diving behavior on a wide variety of odontocete species.

APPROACH

Task 1: Blue whale behavioral response study:
We evaluated the behavioral response of blue whales to intense ship noise and close ship approach using suction-cup attached acoustic recording tags and GPS Fastlock location tags. The proximity of shipping routes into southern and central California ports with predictable blue whale feeding grounds makes this an ideal location of the study of the impact of intense low-frequency noise on whale behavior. Field effort has been conducted for project since 2008. Past effort focused on the Santa Barbara Channel where shipping lanes pass through areas of frequent use by blue whales (Figure 1). Ship traffic use of the channel changed after the California Air Resources Board (CARB) rules in July 2009 mandating use of cleaner fuels within 24 nmi of shore resulted in many ships abandoning the shipping lanes through the channel (Law 2009). In 2010, we transitioned a portion of our operations to the shipping lanes off San Francisco near the Farallon Islands as predictable sightings of blue whales in the shipping lanes there made for an opportunity to work with both ships and whales. In 2011, we shifted our southern California effort further south, just outside the ports of Los Angeles and Long Beach where vessels taking varied routes around the Channel Islands converge, though are generally travelling slower (12 knots) than in areas further from the ports. In 2012, some of the commercial ship traffic returned to the Santa Barbara Channel and field efforts were split between the Santa Barbara Channel and the LA/Long Beach area.

Acoustic data collected by the B-Probe and Acousonde are analyzed to determine the presence and spectral characteristics of sounds produced by the whales and the ambient noise level prior to ship approach. Because of high levels of flow noise present in the acoustic tag records it is not always possible to measure the received sound level of the passing ship. During most behaviors the animal is swimming, therefore flow noise is usually high and broadband (150 dB and 0-1,000 Hz). For this reason most analyses are now based on ship proximity and speed, and with reference received levels measured for different ship types from seafloor recorders, rather than on the received level measured by the tag. Close approaches during quiet periods in the tag record do allow for direct measures of received level of the ship on occasion.

Dive depth and body orientation are measured by the sensors on the tag, and additional behavioral variables are derived from the auxiliary sensors, including acceleration, fluke rate, and feeding behavior, such as the presence of vertical or horizontal lunges. These behavioral measures are used to describe swimming mechanics, which may be used to derive energy expenditure (Goldbogen *et al.* 2006). Kinematic data for the tag deployments with a close ship passage of <1000 m prior to the 2011 field season were summarized and presented as deviations around the mean (or anomaly) in previous reports. Behaviors analyzed included dive behavior (duration, number of lunges), surface behavior (durations, number of breaths). Position data from the MK10 are used to evaluate fine-scale movements of the animals within and near the shipping lanes. Nighttime movements and behavior which cannot be effectively monitored by the research team are recorded on the MK10 for later evaluation of close ship approaches and behavioral changes during this period.

Task 2: Filed testing the new Bioacoustic Probe (Acousonde):
Tags are placed on various cetacean species off Southern California and Hawaii in conjunction with ongoing survey and tagging efforts. Off Southern California, our efforts are coordinated with visual and acoustic surveys underway as part of the SoCal BRS and our ship strike work (described as part of this report). Acoustic and dive data are analyzed as described above to assess the quality of the data collected by the new tag and to assess vocal and dive behavior of specific species.

WORK COMPLETED

Task1: Blue whale behavioral response study:
We deployed suction-cup attached acoustic and GPS tracking Fast-loc tags onto blue whales within and around the Santa Barbara Channel shipping during 6 dedicated field efforts and 3 collaborative field efforts between since August 2008 and August 2012. This includes successful deployment of 45 Mk-10 GPS tracking tags, and 36 acoustic tags. Acoustic tag deployments include use of BProbe (19), Acousonde (8), and D-Tag (9). Although most tags were deployed during field efforts specifically dedicated this project, 32 tags (19 MK10s, 13 acoustic tags) were deployed in conjunction with the SoCal Behavioral Response Study (BRS) when that project was operating within or near shipping lanes. Eleven blue whales were tagged with both an acoustic tag and MK10 GPS tracking tag simultaneously providing both detailed movement and acoustic datasets. Two 2012 deployments in coordination with the SoCal BRS used DTags enabled with GPS tracking capabilities. Average deployment duration for MK-10 tags was 8.0 hrs., and for acoustic tags was 4.8 hrs., while maximum deployment duration was Although this project focused on blue whales, tags also were deployed on 3 humpback whales, one sperm whale, and one fin whale, making a small contribution to our understanding of the movements of those species near the shipping lanes.

Regulatory changes instituted by the California Air Resources Control Board (CARB) required a change in geographic focus during the study. Deployments in 2009 focused within the shipping lanes north of the Channel Islands where ships travel through blue whale foraging grounds at high speed.

Tagging efforts since 2010 were largely shifted to the eastern channel, as the CARB rules requiring ships to switch to clean fuel within 24 nmi of California coast resulted in many ships approaching the Ports of Long Beach and Los Angeles from south of the Channel Islands. Ships tend to travel more slowly in the eastern channel as they approach the port, resulting in sampling a different condition than whales would face within the shipping lanes further to the north and west. Further, while several deployments were conducted within the shipping lanes, whale distribution often forced us to deploy on whales just outside or within a few miles of shipping lanes, enabling evaluation of whale day versus night movement patterns and examination of the vulnerability of whales to ship strike during the night.

The collection of deployments conducted as part of this study has resulted in new information on many aspects of blue whale response to ship noise and close ship approach, including:

1. Examination of vocal response related to close ship approach (2009 and 2010 reports)
2. Evaluation of noise levels during close ship approach (2010 and 2011 reports)
3. Examination of the frequency of close ship approach using combined GPS and ship-based AIS datasets (Figure 1; 2011 and 2012 reports)
4. Evaluation of animal movement at night and the relative risk of ship strike at night versus day (2011 and 2012 reports)
5. Examination of non-vocal behavioral response to close ship approach

Many of these results have been reported in prior project reports. Here we focus primarily on new analyses and findings.

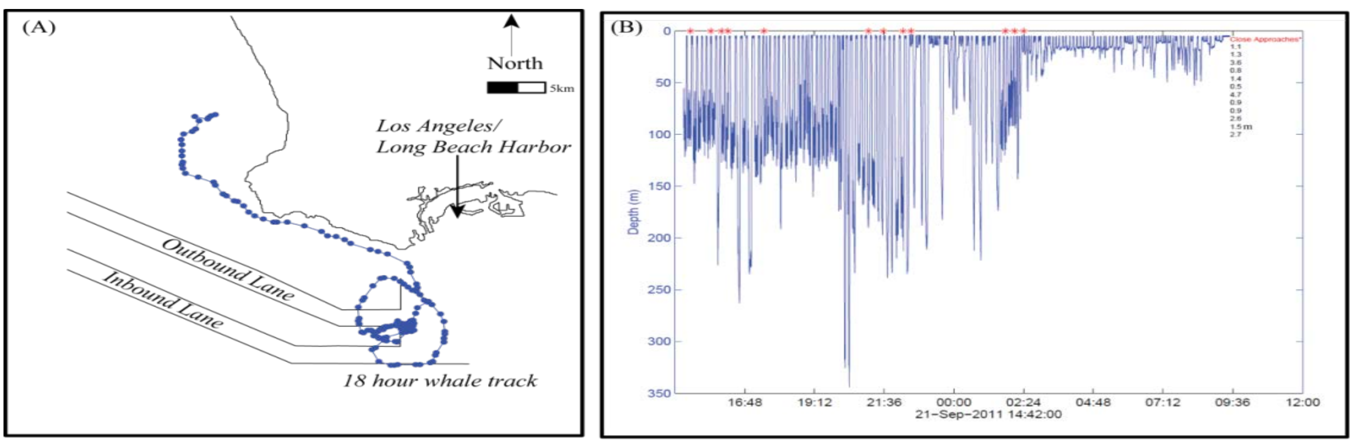

Figure 1: Mk 10 tag deployment on 21 September 2011 and examples of close approaches with large ships. The tag recorded for 18.6 hours. (A) Interpolated track of blue whale with Mk10 GPS tag points indicated by dots. (B) Dive profile of the whale with red stars indicating close approaches identified from combining mk10 and AIS data. Distances of each close approach are shown on the right.

Task 2: Field testing the new Bioacoustic Probe

A type 3A Acousonde was tested on blue whales off Southern California and on a pilot whale off Hawaii in 2011. In early 2011, the new streamlined form factor (Acousonde 3B) became available and was tested during several deployments on blue whales off southern California (as part of task 1) in 2011 and 2012 and on a spotted dolphin off Hawaii in spring 2011. Deployment on calling blue whale has enabled the comparison of the low frequency acoustic datasets collected between the BProbe and the Acousonde (2011 report). More detailed calibration of the acoustic systems within the Acousonde was conducted in 2012 at the Navy calibration facility TRANSDEC, where the frequency response both low power and high frequency channels was evaluated (Wiggins 2013). Further the directional response, or beam pattern, of the high frequency channel was assessed at 25kHz, 50kHz, and 75kHz to understand what impact the physical structure of the tag has on system response at various incident angles. Additionally, the datastream from the Acousonde auxiliary sensors has been incorporated into the software TrackPlot, enabling evaluation of 3-dimensional movement of the tagged animal while underwater. Improvements to the suction cup and pole attachment head design have also been accomplished as part of this study, likely resulting in longer deployments on large whales.

RESULTS

Task 1: Blue whale behavioral response study
Diel variation in movement and diving behavior
Over 25 deployments from acoustic and MK-10 tracking tags were used to evaluate variation in blue whale behavior between night and day. Dives at night are much shorter and shallower than during the day, placing whales at greater risk of ship strike at night if witin the shipping lanes. Increased time at the surface and horizontal movement patterns of blue whales at night compared to the day suggest greater vulnerability to ship strikes at night (Figure 2). At the depth of an average ship draft (15m), the probabilities of srike if a ship passed overhead are 0.35 during the day and 0.57 at night.

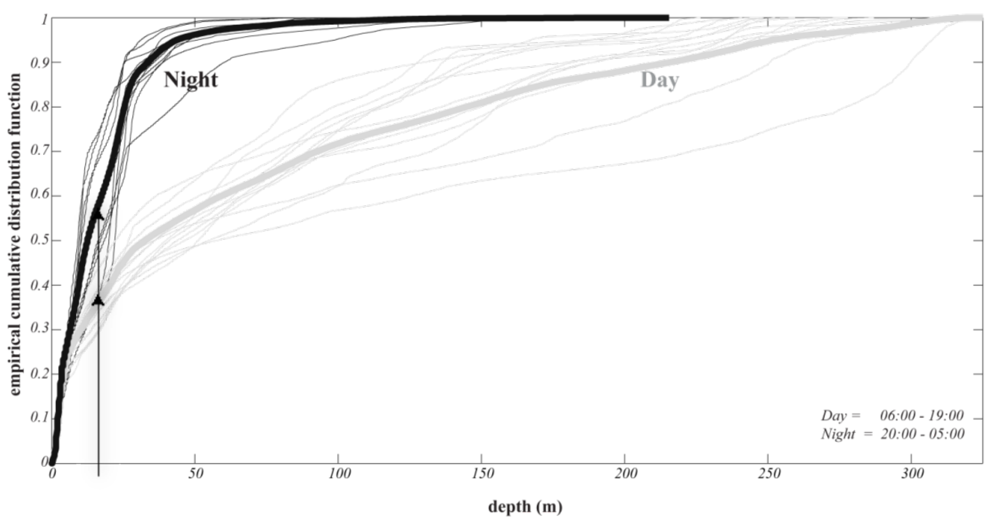

Figure 2: Cumulative distribution functions for the depth of the whales, given different hours of the day. The colors represent the different hours of the day. Arrows indicate average draft of a large ship (15 m).

Non-vocal response to close ship approach
Evaluation of the dive and movement datasets collected during this study have revealed that blue whales appear not to exhibit any lateral avoidance to fast traveling ships, even at close (~100-400m) range (Figure 3), but do show vertical response. An "avoidance dive" has been described based on blue whale response during close ship approach, approach by whale watch vessels, and exhibited immediately after tag application (Figure 4). The vertical reaction of whales appears to be a slower descent than during foraging dives, putting whales at higher risk of stike if a ship were to pass

overhead. These data were integrated into a model to evaluate the maximum ship speed that would allow a whale time to avoid an oncoming ship. Model parameters included hydrodynamic forces around ships and the observed whale avoidance behavior. Our analysis suggest that relatively slow descent rates on avoidance dives requires slower ship speeds to avoid collision (Figure 5). Our tag data also reveal increases in surface time by some whales after close approaches by fast moving ships, although this response is less evident in regions with slower moving ships.

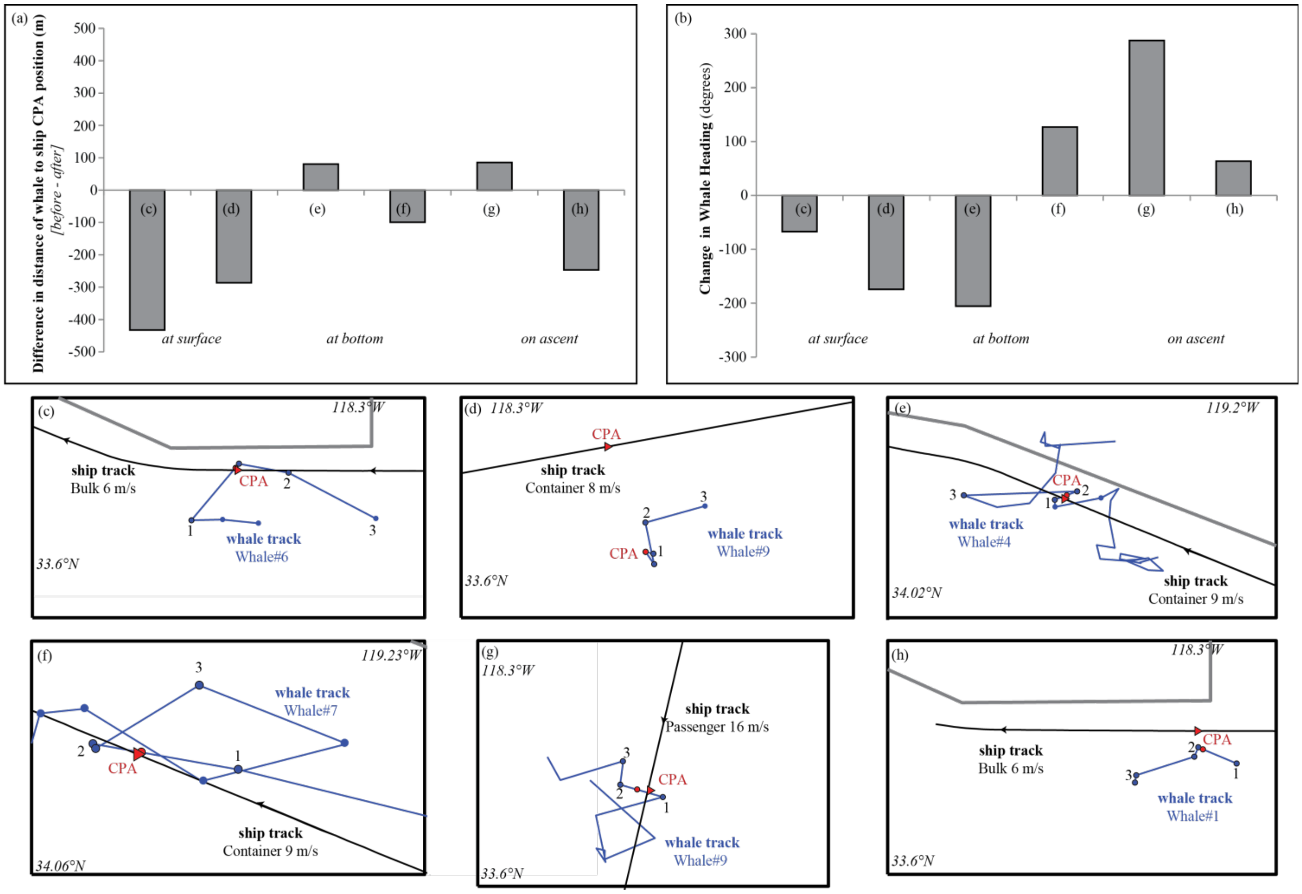

Figure 3. Summary of horizontal surface movements of whales during close ship passages of <300 m. (a) Difference in distance of the whale to the ship CPA position, negative values indicate the whale moved closer after the CPA. (b) Change in the heading of the whales before and after CPA. Headings were calculated as the direction to the next surface period. The x-axis indicates where the whales were during the CPA. Panels c-h detail whale movement at the time of CPA (indicated by red dot for whale positions and red triangle for ship position). The numbered positions indicate the order of surface periods (1= before, CPA = red, 2= after and 3=2 surface periods after CPA).

Task 2: Field testing the new Bioacoustic Probe (Acousonde)

The Acousonde 3A was used during four deployments on blue whalesd and a pilot whale before suffering a break in the infrared sensor, making the unit unusable. Several 3Bs were tested on blue whales and a spotted dolphin. Several of the 3B attachments in 2011were short and may have reflected problems getting a good attachment due to the shape of the griper head holding the tag. The attachment head was modified for 2012 and the two deployments in 2012 resulted in intermediate attachment durations of 4 and 8.7 hours possibly reflecting better attachments. The first deployment of the

Acousonde 3B on spotted dolphins was a huge success, as it demonstrated the benefit of the smaller and more streamlined form-factor of the tag. This deployment was the longest known suction cup tag deployment on a spotted dolphin and it collected valuable data on the vocal and dive behavior of an individual spotted dolphin during intense troll fishing by eight different fishing boats. Further details on the data collected during this deployment are available in the 2011 project report.

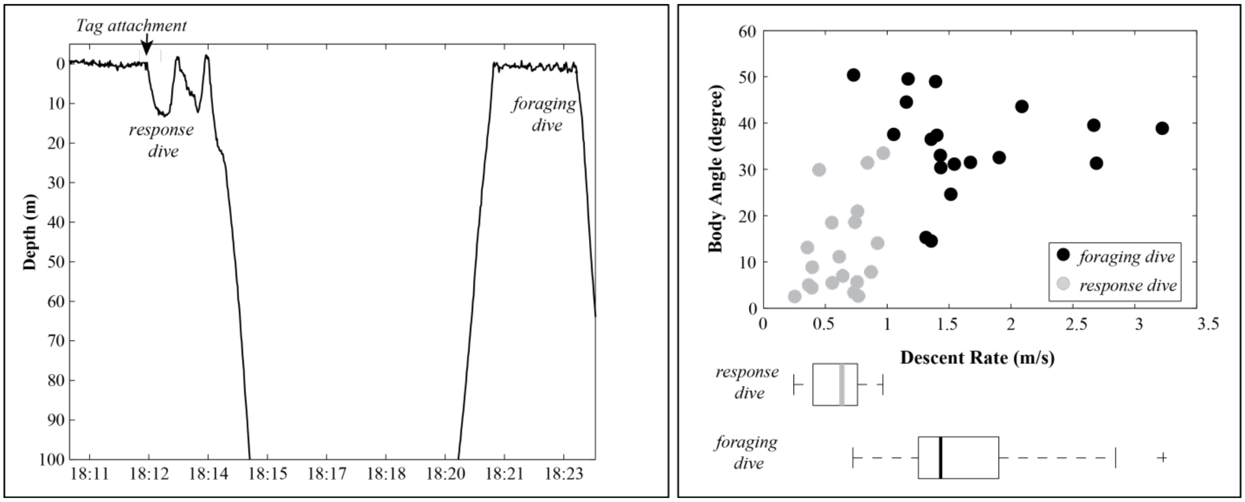

Figure 4: Blue whale response to suction-cup tag deployments. Left panel shows an example of a whale dive reaction during a successful tag attachment followed by a deep foraging dive. The right panel illustrates the relationship between descent rate and body angle for response and foraging dives. Box plots along x-axis show average descent rates for all response dives and foraging dives. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually at plus signs.

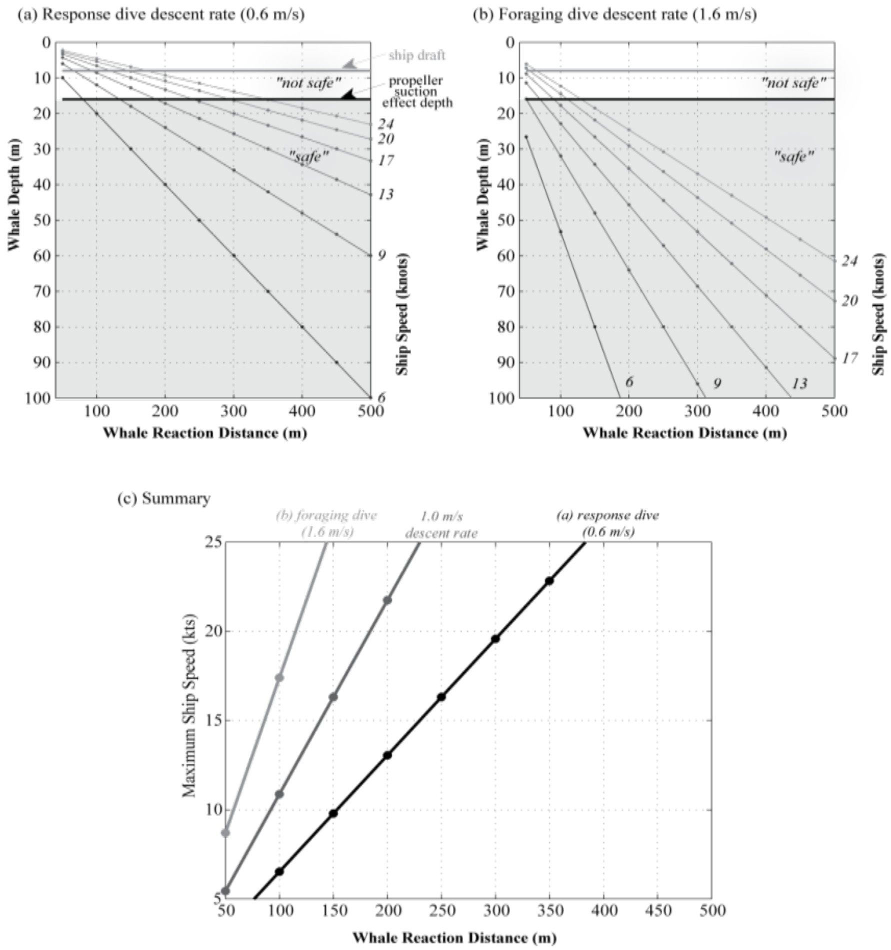

Figure 5: Modeled depth of whales considered safe from collisions based on reaction distances and ship speeds for descent rate of the response dive (a) and foraging dive (b). Curves represent different ship speeds. c) Distances at which whales would need to react to "avoid" collision with the ship as a function of different descent rates shown in (a), (b) and for 1.0 m/s.

The acoustic system in four Acousonde 3Bs were calibrated at the Navy facility TRANSDEC in fall 2012, with test setup, tag specification, and measured reponse details available in Wiggins (2013). The measured repsonse of the low-power acoustic system is similar to the tag specification below 1kHz for all tested tags, but shows increasing variability and deviation from the expected response above 1kHz (Figure 6). All four tested tags show a significant dip (more ~6dB and more than 10dB respectively) in their frequency response at 2kHz and 6kHz. Note the sensitivity for tag A (B006) is different than for other tags given use of a different low-power hydrophone.

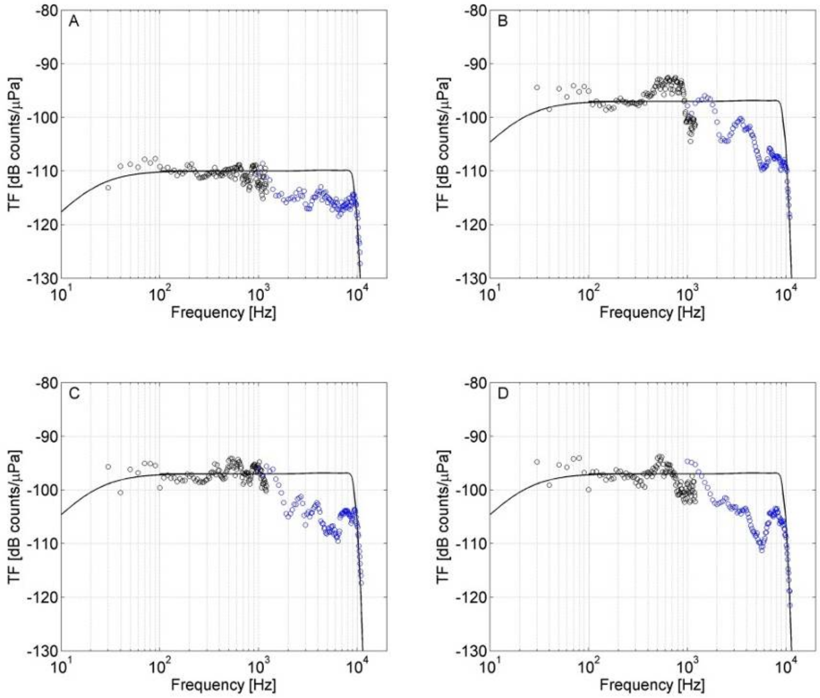

Figure 6. Frequency response of the low-power, low-frequency channel for Acousonde 3B tags A) B006, B) B008, C) B013, and D) B014. The expected frequency-response based on electronic design specs is shown as solid black. The measured sensitivity at each measured frequency is represented by open circles during two series of transmissions, the first (black) from 30 Hz to 1.2 kHz, and the second (blue) from 1-10.7 kHz.

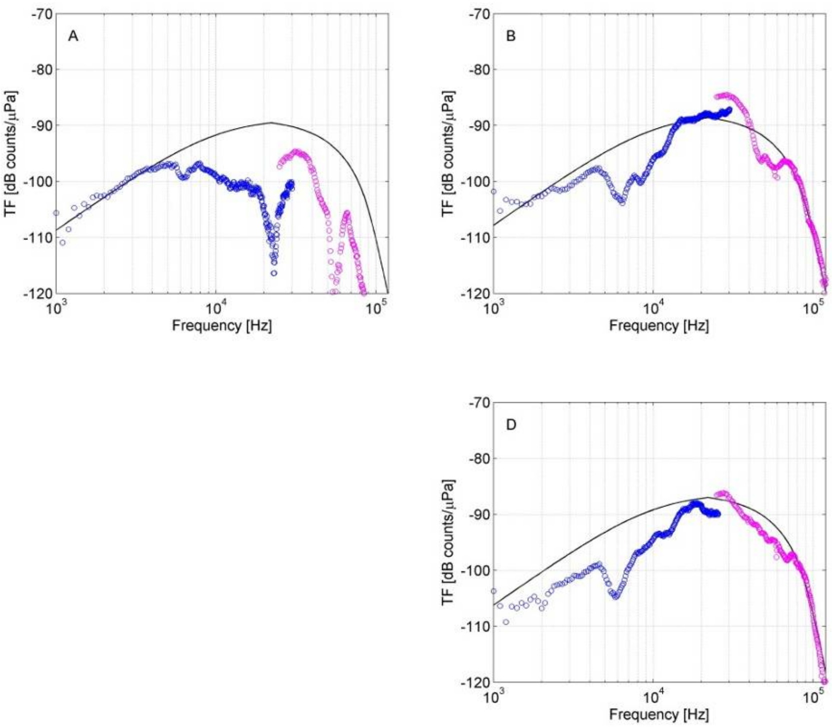

Figure 7. Frequency response of high-frequency channel for Acousonde 3B tags A) B006, B) B008, and D) B014. The high-frequency response of tag C) B013 was not tested. The expected frequency-response based on electronic design specs is shown as solid black. The measured sensitivity at each frequency is represented by open circles during two series of transmissions, the first (blue) from 1-12 kHz, and the second (purple) from 11.5-100 kHz.

The overall shapes of the measured high-frequency response follow the shape expected given tag specifications, with best agreement between 1–5 kHz for tags A and B. The 1-5 kHz response for tag D is about 3 dB lower than expected (Figure 7, blue circles). At frequencies above 10 kHz, the measured response is more variable within and between tags. All three tags have notches around 6 kHz, and tag A has a large notches around 23 kHz and 55 kHz. Other deviations from the specified response are within 5 – 10 dB, significant enough to warrant caution when calculating received levels from these tags using the specified frequency response.

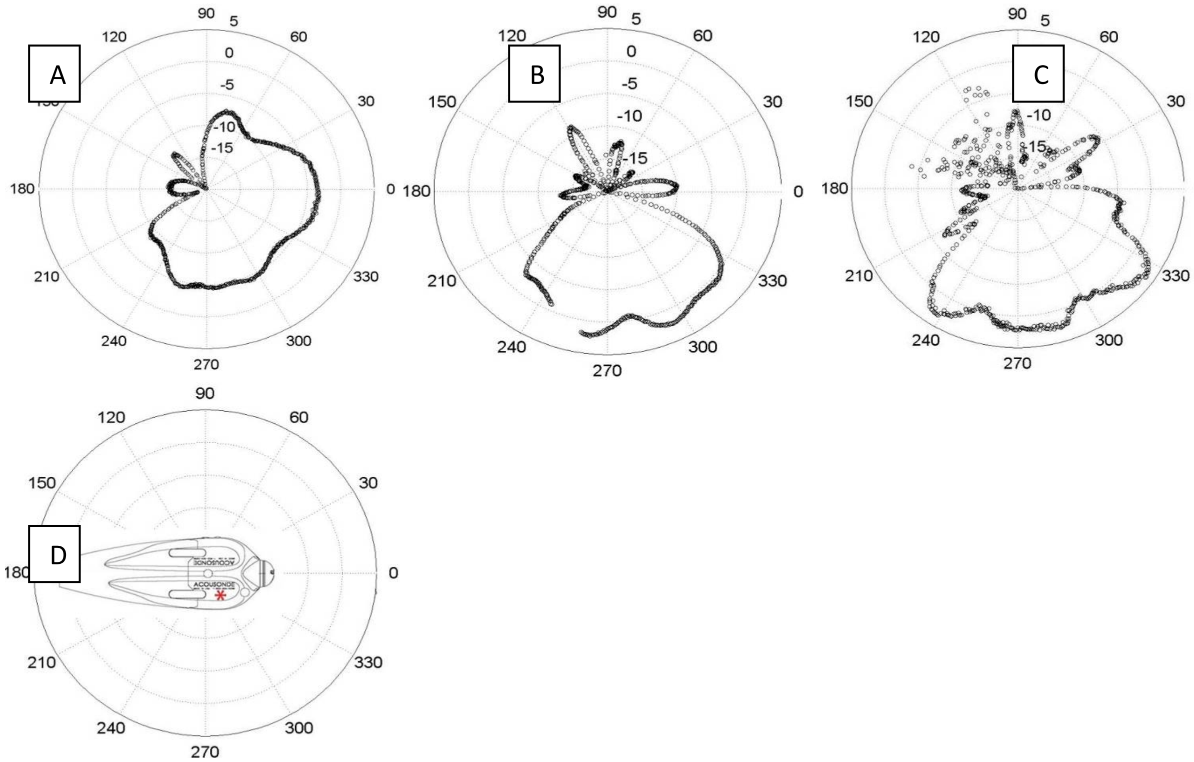

Figure 8. Short-axis beam pattern of tag B010 measured at A) 25 kHz, B) 50 kHz, and C) 75kHz. Panel D shows the orientation of the tag relalative to the transducer for reference. The 0 dB response is the corrected received level following frequency response tests for the provided frequency.

The beam pattern of tag D was produced using both a short- and a long-axis rotation test (Figures 8 & 9). Form short-axis rotation tests, at 25 kHz, the -5 dB beam width was about 135º wide from about 245º to 20º; whereas for both 50 kHz and 75 kHz, levels are above -5 dB for a width of about 110º from approximately 225º to 335º which puts the center of the beam around 280º for 50-75 kHz, near the location of the hydrophone within the tag (Figure 8). In the long-axis beam pattern test, at 25 kHz, the -5 dB beam was about 260º wide from 200º to 300º around clockwise; whereas, for both 50 kHz and 75 kHz the -5 dB beam width was approximately 285º from about 225º to ~ 300º with more peaks and notches for the 75 kHz test. The integrated syntactic float and the battery case resulted in significantly reduced and complex response at incident angles passing past those components. Great care will be needed to estimate received levels from the Acousonde, including integration of the accelerometer response and the 3-dimensional position of the tagged animal at the time of the received signal. Further, use of the tag D beam pattern may be inappropriate for other tags given the variation in frequency response among tags.

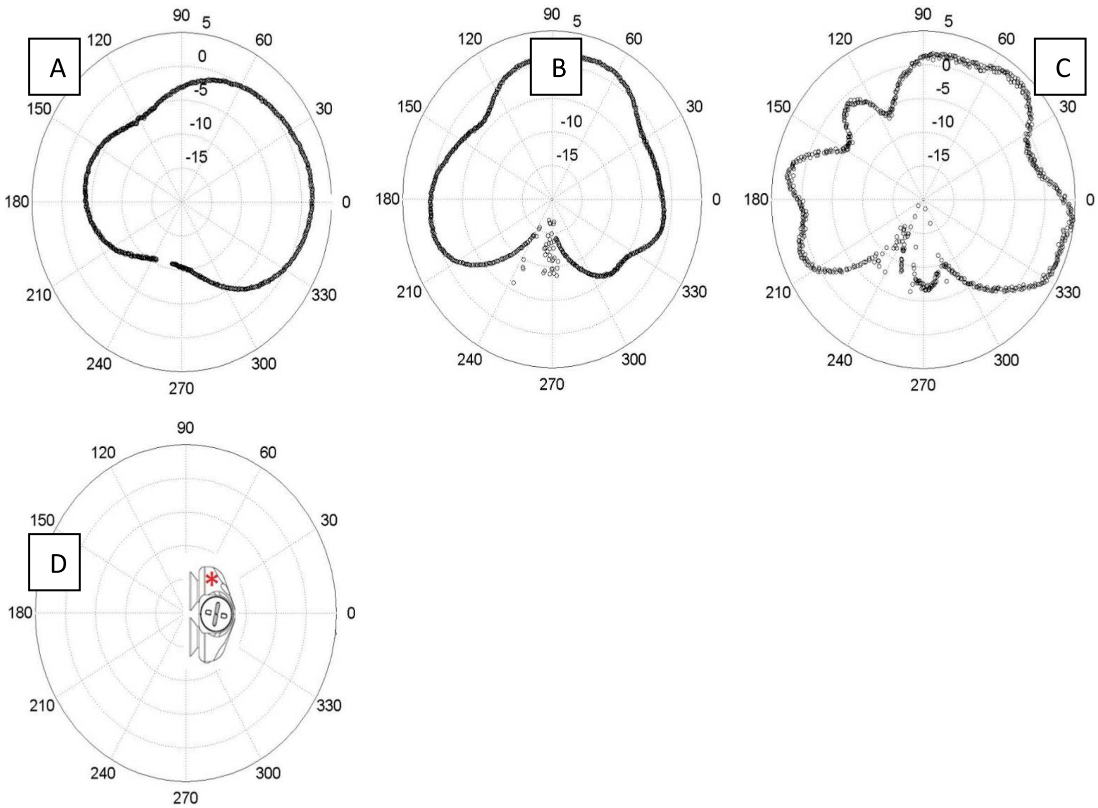

Figure 9. Long-axis beam pattern of tag B010 measured at B) 25 kHz,C) 50 kHz, and D) 75kHz. Panel A shows the orientation of the tag relalative to the transducer for reference. The 0 dB response is the corrected received level following frequency response tests for the provided frequency.

Acousonde accelerometer, depth, and compass data sets have been intergrated into trackPlot software allowing for 3-D visualization of the tagged animal while underwater. An example is illustrated in Figure 10 with data from a lunge-diving blue whale.

IMACT/APPLICATIONS

Task 1: Blue whale response to ships

The results of our tagging and monitoring studies have provided new information especially important for evaluation of ways to reduce the impact of ship strikes. Our information on whale occurrence in and around shipping lanes has proved valuable in evaluating the placement of shipping lanes off southern and central California. In 2012 proposed changes to the shipping lanes leading to Los Angles, Long Beach and San Francisco are going before the International Maritime Organization partly as a result of some of our data. Information on the behavior and movements of blue whales at night and how this makes them more vulnerable to ship strikes and their reaction to ships has been important in the evaluation of ways to reduce ship strikes including the 2012 recommendations of a Joint Working Group on ship strikes and ship noise (Joint Working Group 2012) that represents an ambitious plans for the reduction of ship strike and ship noise impacts on whales off central California.

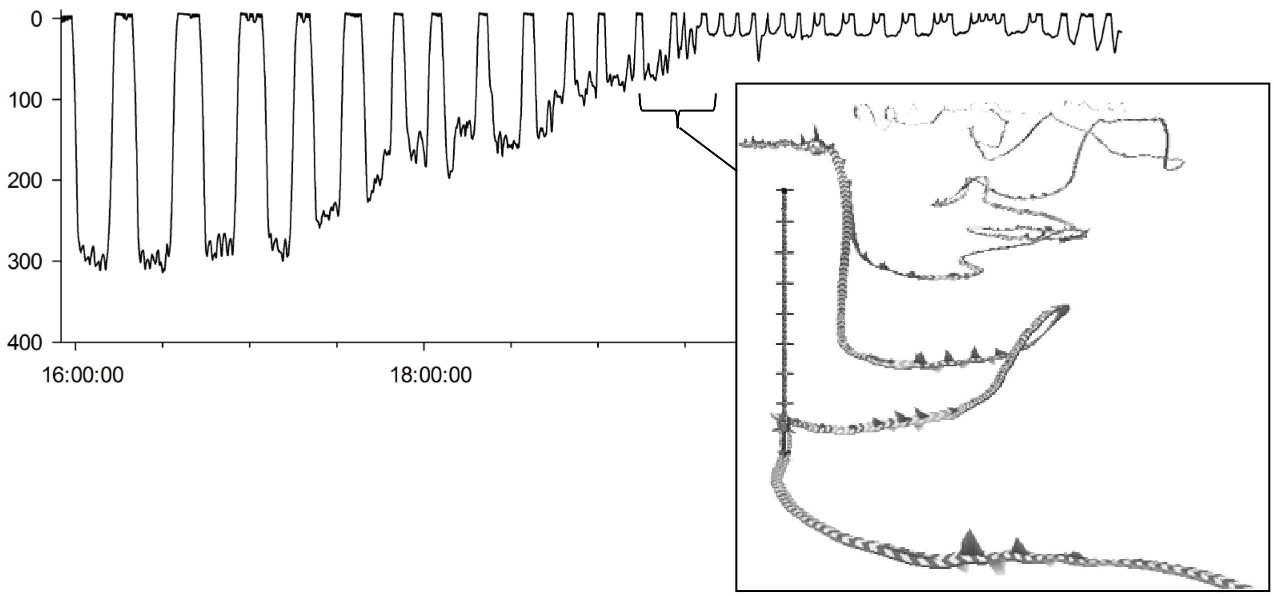

Figure 10. Blue whale dive profile shown in traditional view and with 3-D detail from TrackPlot.

Task 2: Field testing the new Bioacoustic Probe:
The Acousonde acoustic recording tag includes improved acoustic and auxiliary sensors. Animal orientation can be assessed in 3-dimensions, as well as dive depth, with all sensors capable of 20Hz or higher sampling. Acoustic calibration of the tag suggests deviations from the provided specifications, including notches in the frequency response at specific frequencies within all tested tags. Further, beam pattern tests reveal significant shadowing at some angles by the integrated syntactic foam float and the battery case, as well as other components. These results suggest the accelerometer should also be calibrated so that received levels can be corrected based on the orientation of the tag relative to the acoustic source. Complex patterns at some receive angles suggest measurements of absolute received level may not always be possible. Some tag failures during our testing missions suggest some technical improvements are still needed.

RELATED PROJECTS

Task 1: Blue whale behavioral response study:
Several agencies and instutions have contributed to the greater goals of this project. Support has been provided by the Channel Islands National Marine Sanctuary who provided time on their vessel R/V Shearwater in all years of this study. Additional funding has been provided by NMFS Marine Mammal Conservation Division. High-Frequency Acoustic Recorders (HARPs) were deployed in and around the Santa Barbara Channel by Scripps Insitution of Oceanography with support from NOAA Fisheries Acoustics Program. The HARPs have provided valuable data on the spectral and sound level properties of individual ships (see publications list). The SoCal BRS field operations have provided valuable deployment opportunities in and near the shipping lanes that served the goals of both the BRS and this project.

PUBLICATIONS

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